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Original paper

Monte Carlo evaluation of glandular dose in cone-beam X-ray computed tomography dedicated to the breast: Homogeneous and heterogeneous breast models

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ABSTRACT

Purpose: In cone-beam computed tomography dedicated to the breast (BCT), the mean glandular dose (MGD) is the dose metric of reference, evaluated from the measured air kerma by means of normalized glandular dose coefficients (DgN_{CT}). This work aimed at computing, for a simple breast model, a set of DgN_{CT} values for monoenergetic and polyenergetic X-ray beams, and at validating the results vs. those for patient specific digital phantoms from BCT scans.

Methods: We developed a Monte Carlo code for calculation of monoenergetic DgN_{CT} coefficients (energy range 4.25–82.25 keV). The pendant breast was modelled as a cylinder of a homogeneous mixture of adipose and glandular tissue with glandular fractions by mass of 0.1%, 14.3%, 25%, 50% or 100%, enveloped by a 1.45 mm-thick skin layer. The breast diameter ranged between 8 cm and 18 cm. Then, polyenergetic DgN_{CT} coefficients were analytically derived for 49-kVp W-anode spectra (half value layer 1.25–1.50 mm Al), as in a commercial BCT scanner. We compared the homogeneous models to 20 digital phantoms produced from classified 3D breast images.

Results: Polyenergetic DgN_{CT} resulted 13% lower than most recent published data. The comparison vs. patient specific breast phantoms showed that the homogeneous cylindrical model leads to a DgN_{CT} percentage difference between −15% and +27%, with an average overestimation of 8%.

Conclusions: A dataset of monoenergetic and polyenergetic DgN_{CT} coefficients for BCT was provided. Patient specific breast models showed a different volume distribution of glandular dose and determined a DgN_{CT} 8% lower, on average, than homogeneous breast model.

1. Introduction

Three-dimensional (3D) X-ray breast imaging techniques have been developed having in mind the limits of projection mammography related to the superimposition of tissues, which may affect the detectability of mass lesions. Indeed, tomographic techniques like X-ray computed tomography (CT) are known to reproduce with high contrast the body or organ 3D anatomy. Digital breast tomosynthesis (DBT)—which produces pseudo-tomographic 3D images of the compressed breast with anisotropic resolution [1–4]—is routinely adopted in the clinic for second level examinations; clinical reports for its application in screening studies have been presented recently [5]. In the last few years, following the techniques and scanning strategy initially proposed by Boone et al. [6] and Chen and Ning [7], cone-beam CT dedicated to the breast (BCT) [6–13] received regulatory approval in USA and marketing licence in the European Union (for a recent review, see [14]). BCT produces sectional images of the uncompressed breast with isotropic resolution and excellent contrast sensitivity [8,9]. As a fully 3D technique, it eliminates tissue superimposition, and it may reduce the patient discomfort due to the absence of breast compression [8], as opposed to mammography and the limited-arc tomographic technique of DBT.

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As regards the imaging radiation dose, the dose metric, both in 2D and in 3D X-ray breast imaging, is the mean glandular dose (MGD) (mGy), i.e. the ratio of the energy absorbed in the whole volume of breast glandular tissue to its mass. The MGD is adopted for cancer risk estimates in mammography [15] as well as in DBT [1,16], and it is considered for image quality comparisons in such breast imaging procedures [17]. In two-view digital mammography, an average MGD value of 3.7 mGy has been reported [15]. The concept of MGD was introduced as a figure of merit for comparing the radiation dose among different breast imaging techniques [18] and the energy absorbed in glandular tissue, E_g, was considered the meaningful quantity for radiation risk estimates. In Hammerstein et al.'s words, "Detailed information will have to be obtained on the amount and distribution of gland tissue in many individual cases before E_g can be applied properly to the problem of individual risk" [18]. Such detailed information is still lacking in the literature, and collective risk estimates in breast imaging are based on the MGD metric, on the assumption of a homogeneous distribution of the gland in the breast [19]. This last is well recognized as an unrealistic condition, given the wide variability of the total gland mass and its location in the breast volume, though the gland is usually considered as concentrated towards the centre of the breast [20]. Models of radio-induced cancer risk in X-ray breast imaging based on patient-specific anatomical data will need the assessment of the 3D glandular dose distribution.

Since measurements of the absorbed energy or of the glandular mass are not possible *in vivo*, in each exam the MGD is estimated for a breast model, from Monte Carlo (MC) simulations of the imaging setup. In these estimates, the specific anatomy of the patient is not modelled, apart from measurement of its compressed breast thickness and estimation of its average glandular fraction by weight (i.e. the ratio of the total glandular mass to the mass of adipose and fibroglandular tissue in the breast).

The protocols for MGD estimates in 2D mammography are well defined and routinely adopted [21–24]. Recently, a protocol which includes guidelines for dose estimation in DBT has been produced [25]. In addition, a joint AAPM/EFOMP task group[1] is dedicated to defining a protocol for MGD estimates in screening and diagnostic mammography and DBT. In all protocols, the simulations produce dimensionless coefficients of MGD per unit air kerma (mGy/mGy), so-called coefficients of normalized glandular dose (DgN) or the triad of coefficients (c, g, s) as proposed in Refs. [21–24].

Cone-beam BCT (also in conjunction with mammography) is being investigated clinically for breast cancer diagnosis [8,9]. The MGD in each BCT scan can be derived by adopting suitable DgN_{CT} coefficients, as conversion factors from the air kerma at the scanner isocentre to the MGD [12,26–29]. For a given breast, DgN_{CT} coefficients depend on the breast dimensions (diameter at the chest wall and length) and breast glandularity as well as on the X-ray beam spectrum. Boone et al. [26] modelled the breast as a cylinder of homogenous mixture of glandular and adipose tissue enveloped in a layer "equivalent" to 4-mm thick skin. They provided (via MC simulations) polyenergetic DgN_{CT} coefficients for their in-house developed BCT scanner. Thacker and Glick [27] used a model similar to that proposed by Boone et al. [26] (cylindrical shape and 4-mm thick skin) and studied the impact of different assumptions. In particular, they investigated the impact of modelling the breast as a semi-ellipsoid and introduced the breast length as a parameter for the calculation of the monoenergetic DgN_{CT} coefficients. Moreover, they investigated the influence of using a skin of 2-mm thickness instead of 4 mm. Indeed, the skin thickness ranges between 0.5 mm and 2 mm [30] rather than the 4–5 mm adopted in dosimetric protocols for MGD estimates [19]. Skin thickness measurements from 3D images of the breast indicated an average value of 1.45 mm [31,32]. For this reason, Sechopoulos et al. [28], in the determination of DgN_{CT} coefficients for a Koning Corp. cone-beam BCT apparatus (http://koninghealth.com/), modelled the breast with a semi-ellipsoidal shape enveloped in a 1.45 mm layer mimicking the skin. The same shape for the pendant breast was adopted in Ref. [33], where the authors showed – via MC simulations and laboratory measurements on PMMA phantoms – the highest uniformity of the dose spread in the breast volume in a BCT scan, with respect to two-view mammography.

In addition to 2D and DBT imaging [34], BCT with a monoenergetic, parallel beam from a synchrotron radiation source and the patient in prone position is under investigation at the Elettra facility (Trieste, Italy) [35–38]. In that experimental project, the patient is placed on a rotating and vertically translating bed with her breast freely hanging from a hole. The use of a synchrotron radiation beam implies that only a thin section (few mm in the vertical direction) of the breast can be imaged during a rotation; this specific irradiation geometry led to the definition of two new dose metrics – MGDt and MGDv – which take into account the dose to the total glandular mass in the organ and to the sole irradiated volume, respectively [39]. This strategy for MGD definition in partial breast irradiation was adopted also when investigating the MGD for spot mammography [40].

Recent papers [41,42] showed that, in mammography, the assumption of homogeneous glandular and adipose mixture within the breast may lead to an average MGD overestimation of 30%. This overestimation decreases to 10% in the case of BCT at 49 kVp (i.e. the tube voltage of the Koning Corp. apparatus) and it is even lower for higher X-ray energies [41]. Yi et al. [29] showed similar results by adopting 3D images of mastectomy breast specimens. Hence, they compared, via MC simulations, dose estimates with structured breast digital models and simple homogeneous breast models, showing slight differences. In addition, Hernandez et al. [43] produced DgN_{CT} coefficients by adopting digital breast models, which reflect the real breast silhouette, but not the real glandular distribution. They showed that these models do not lead to large MGD differences when compared to results for cylindrical breast models.

This work aimed at defining a simple homogenous breast model for DgN_{CT} evaluation and providing a complete monoenergetic ($DgN_{CT}(E)$) and polyenergetic ($pDgN_{CT}$) coefficients dataset for MGD estimates in cone-beam BCT. Here the pendant breast, modelled as a homogeneous mixture of adipose and glandular tissues, is a cylinder with a 1.45-mm thick skin layer. $DgN_{CT}(E)$ were computed for X-ray photon energies up to 82.5 keV and they were fitted with polynomial curves. Fitting coefficients were released for its usage in applications with generic produced spectra or for applications which employs monoenergetic X-ray beams. $pDgN_{CT}$ were computed for spectra adopted in the clinical practice. For a fixed anode/filter combination, several coefficients were computed in order to cover a broad range of X-ray beam HVL. To our best knowledge, this work presents values for cone-beam breast CT dosimetry coefficients based on up-to-date breast models in the widest set of parameters (geometry, composition and photon energy) presently available.

Finally, we adopted a series of digital patient-specific breast phantoms derived from clinical cone-beam BCT images – which have the silhouette and the heterogeneous glandular tissue distribution of real breasts – for devising patient specific phantoms. These phantoms were input in the MC simulations and the calculated MGD and glandular dose distributions were compared to those obtained for homogenous cylindrical breast model in order to validate the proposed simple homogeneous model.

2. Materials and methods

2.1. Normalized glandular dose in breast CT

In cone-beam BCT, the MGD is estimated from the air kerma at the scanner isocenter (K) [26–28] as follows:

[1] https://www.aapm.org/org/structure/?committee_code=TG2821/